Predicting deposition of debris flows in mountain channels

LEE E. BENDA
Department of Geological Sciences, University of Washington, Seattle, WA 98195, U.S.A.
AND
TERRANCE W. CUNDY
College of Forest Resources, University of Washington, Seattle, WA 98195, U.S.A.
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An empirical model for predicting deposition of coarse-textured debris flows in confined mountain channels is developed based on field measurements of 14 debris flows in the Pacific Northwest, U.S.A. The model uses two criteria for deposition: channel slope (less than 3.5°) and tributary junction angle (greater than 70°). The model is tested by predicting travel distances of 15 debris flows in the Oregon Coast Range and six debris flows in the Washington Cascades, U.S.A. The model is further tested on 44 debris flows in two lithological types in the Oregon Coast Range using aerial photos and topographic maps; on these flows only the approximate travel distance is known. The model can be used by resource professionals to identify the potential for impacts from debris flows.
Key words: debris flow, deposition, travel, erosion.

Un modèle empirique pour prédire la déposition d'écoulements de débris à texture grossière dans des canaux de montagne confinés a été développé en partant de mesures sur le terrain de 14 écoulements de débris sur la côte nord-ouest du Pacifique, États-Unis. Le modèle utilise deux critères pour la déposition : la pente du canal (moins de 3.5°) et l'angle de la jonction du tributaire (plus grand que 70°). Le modèle a été vérifié en prédisant les distances de parcours de 15 écoulements de débris dans la Chaîne Côtière de l'Oregon et six dans les Cascades de Washington, États-Unis. Le modèle a été de plus vérifié sur 44 écoulements de débris de deux types lithologiques dans la Chaîne Côtière de l'Oregon au moyen de photos aériennes et de cartes topographiques; pour ces écoulements, il n'y a que la distance de parcours qui soit connue. Le modèle peut être utilisé par les professionnels des ressources pour identifier le potentiel d'impacts des écoulements de débris.
Mots clés : écoulement de débris, déposition, parcours, érosion.

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Introduction

Debris flows can form as landslide debris liquifies and moves through steep, confined channels. In the Oregon Coast Range, debris flows have been observed to travel up to several kilometres at speeds up to 10–15 m/s (Benda 1988). The flows increase in volume by entraining additional sediments, water, and organic debris, and deposit this material in channels and on valley floors. This form of mass movement is common in the mountainous terrain of the Pacific Northwest (Oregon to Alaska) and constitutes one of the most damaging forms of erosion in forested watersheds (Swanston 1980; Eisbacher and Clague 1984).

Though debris flows occur naturally, studies in the Pacific Northwest have shown that disproportionately high numbers of debris flows originate from forested lands with a history of timber harvesting and road construction (Swanson and Lienkaemper 1978; Sidle *et al.* 1985). Recent loss of life and damage to property from debris flows in Washington State have resulted in litigation with awards totalling millions of dollars. Debris flows in remote areas have raised concerns about damage to fish habitat and other resources (Swanson *et al.* 1987).

Debris flows tends to become more destructive as their volumes increase with travel distance. They can affect streams and valley floors far from the initial failure. Therefore, methods for predicting initiation sites of debris flows (e.g., Burroughs 1984) should be complemented by methods for predicting depositional sites. Most existing methods for predicting deposition have been partially empirical (e.g., Ikeya 1981; Hungr *et al.* 1984; Mizuyama *et al.* 1984).

In this paper, field observations of initiation, erosion, and deposition of debris flows in the Oregon Coast Range are discussed. These observations are synthesized into a simple empirical model for predicting travel distance and volume of debris flows in confined mountain channels. The model uses measurements of channel geometries easily obtained from field studies, aerial photography, or topographic maps. This model should be useful to resource professionals to assist in the analysis of potential impacts on stream crossings and fish habitat (e.g., Swanson *et al.* 1987). In addition, it could be combined with existing models of debris-flow runout on alluvial fans for hazard zonation (e.g., Takahashi and Yoshida 1979).

The analysis presented here does not apply to water floods laden with woody debris and sediment, as described by Benda (1985) and Benda and Zhang (1989). These debris floods do not exhibit the rheological properties of debris flows.

Study areas

Forty-four debris flows were examined in Knowles Creek, a 52-km^2, fifth-order basin underlain by marine sandstones of the Tyee and Flournoy formations in the central Coast Range of Oregon, U.S.A. (Baldwin 1964) (Fig. 1). The Tyee and Flournoy formations are massive, rhythmically bedded sandstones with interbeds of siltstones and mudstones. The

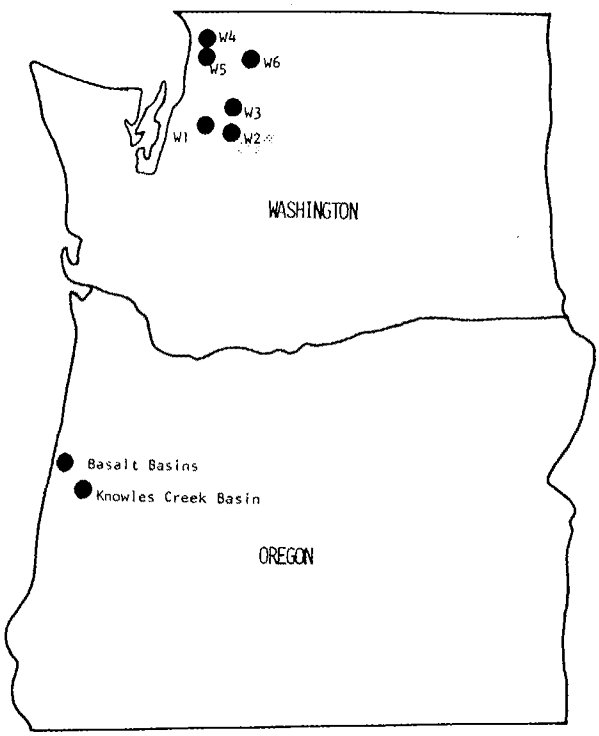

FIG. 1. Study areas.

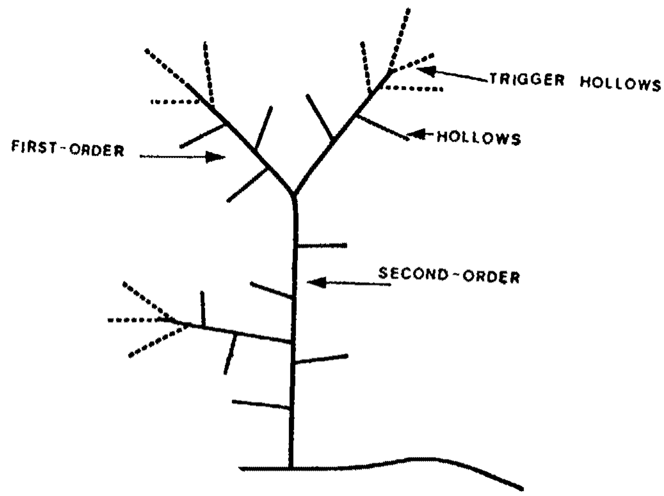

FIG. 2. Hypothetical channel network showing the location of trigger hollows.

area has not undergone glaciation. Hillslopes have angles between 30°–45°, and are sculpted into bedrock hollows (Dietrich and Dunne 1978) or zero-order basins (Tsukamoto *et al.* 1982). These unchanneled topographic depressions are partially or entirely filled with colluvium. Depths of colluvium range from 0.3 to 0.5 m on hillslopes bounding the hollows, and from 0.4 to 3.5 m in the hollows. The bedrock hollows lead into partially vegetated first- and second-order channels with well-defined margins. These channels have beds composed of boulders and cobbles. The depth of the channel sediments ranges from 1 to 3 m and is a source of sediment for scouring debris flows. Benda and Dunne (1987) analyzed the volumes and texture of sediments in first- and second-order channels and concluded that apart from a surface pavement, the sediment consisted of colluvium supplied from the hillslopes and had undergone little or no sorting by fluvial transport.

Annual precipitation of 1600 mm, falling mostly as rain during winter, supports dense stands of Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). The Knowles Creek basin has a century-long history of logging. Intense clearcutting and road construction began in the 1950s and continue to the present. The majority of debris flows originated in clearcuts or adjacent to roads in clearcuts.

An addition 29 debris flows were examined using 1:24 000 aerial photos in basins underlain by marine basalt in the Oregon Coast Range (see Fig. 1). The deeply dissected, linear-shaped basins are formed predominantly in porphyritic basaltic lavas, which are intruded by dikes of aphanitic basalt. Hillslopes and the geometry of valley floors in these basins are similar to those in the Tyee and Flournoy formations. Climate, vegetation, and land-use patterns here are also similar to those of Knowles Creek.

Six debris flows scattered on the western slope of the Cascade Mountains, north of Seattle, WA, and south of the U.S.A.–Canada border (Fig. 1), were also used to test the model. The bedrock geology of this area is dominated by crystalline and metasedimentary rocks, and channels are contained in long, steep, narrow canyons. Extensive sandy outwash and lacustrine deposits originating from continental glaciation during the Pleistocene epoch cover portions of the large valleys.

In Knowles Creek, standard field-surveying techniques were used to measure lengths, widths, and thicknesses of deposits on 29 of the 44 debris flows. Gradients were measured on all channels traversed by the 29 debris flows mentioned above. Velocities of debris flows were estimated by the method of superelevation (Chow 1959). On the remaining 15 debris flows in Knowles Creek and the 29 debris flows in the basalt basins, gradients of deposition sites and travel distances were estimated from 1:24 000 topographic maps with contour intervals of 12 m (40 ft). In the Washington Cascades, gradients of debris-flow depositional sites were measured in the field.

Fourteen of the 44 debris flows in Knowles Creek were used to develop the empirical model. Another 15 debris flows from Knowles Creek and the six debris flows from the Washington Cascades were used to test the accuracy of the model to predict total travel distance. The remaining 15 debris flows from Knowles Creek and the 29 debris flows from the basalt basins in the Oregon Coast Range were used in a further test of the model. In these cases only the approximate travel distance is known from air photos.

Characteristics of debris flows in Knowles Creek:

Initiation

The transformation of a rigid soil mass to a debris flow is not well understood. There are mud lines at failure sites and at the heads of first-order channels, suggesting transformation of the soil mass to debris flow by liquefaction concurrently with failure (Iverson and Major 1986) or by subsequent failure of landslide debris in first-order channels.

In Knowles Creek, in the 36 cases where initiation sites could be identified, 28 were initiated from within bedrock hollows. The remaining eight landslides occurred on relatively planar hillslopes. The significance of hollows in the initiation of debris flows in the Pacific Northwest has been noted elsewhere (Dietrich and Dunne 1978; Reneau and

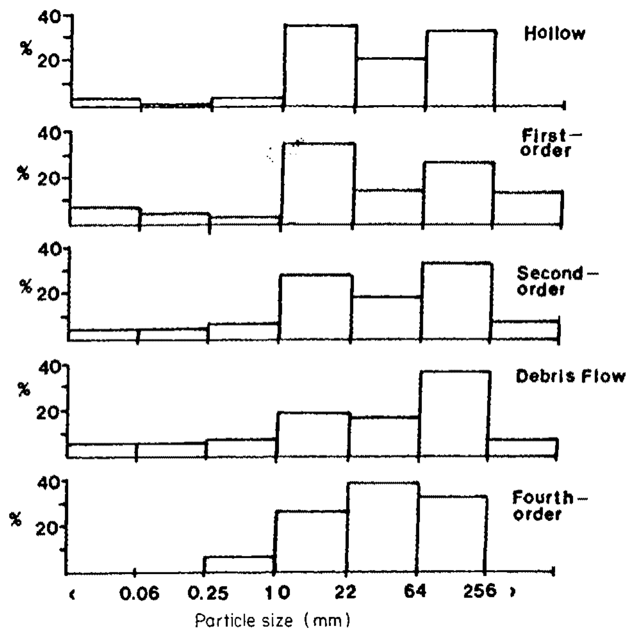

FIG. 3. Sediment sizes from various locations in the Knowles Creek basin.

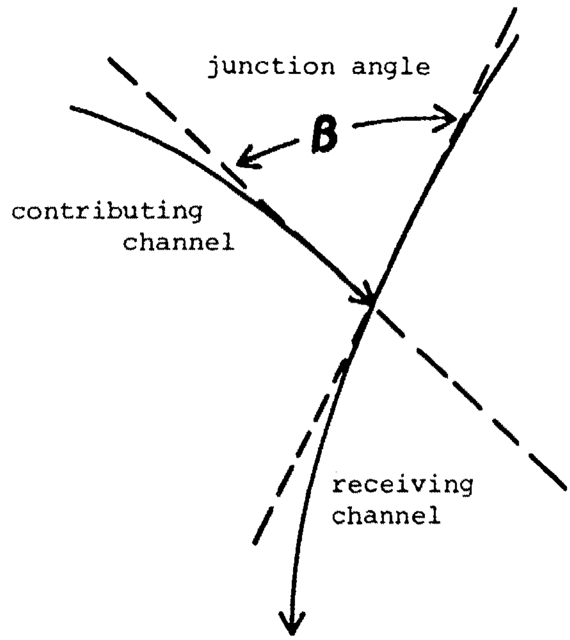

FIG. 4. Geometry and terminology of stream junctions.

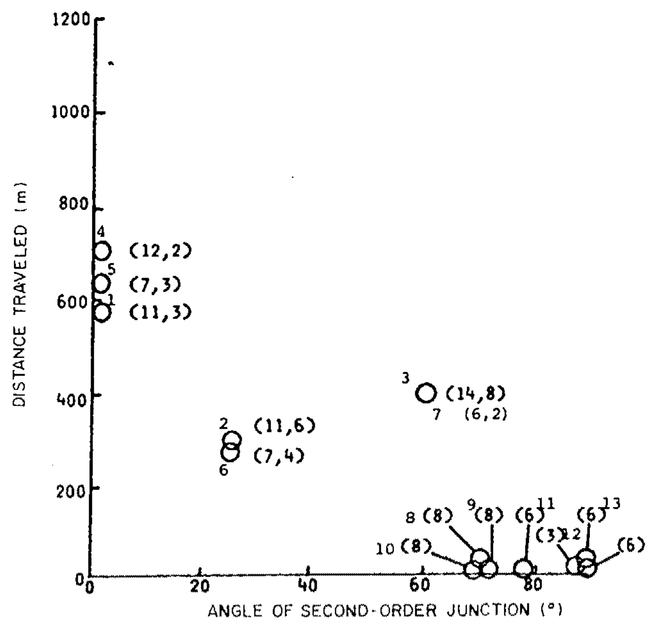

FIG. 5. Relationship between channel-junction angle and travel distance. For data points with two numbers in parentheses, the first corresponds to the slope of the third-order channel where the debris flow first entered. The second number corresponds to the slope of the third-order channel at deposition. For data points with one number in parentheses, the number corresponds to the slope of the third-order channel where the debris flow entered and immediately deposited. Numbers next to data points correspond to debris flows in Table 2.

Dietrich 1987). The density of bedrock hollows averaged 100/km^2; the number of hollows in a first-order basin ranged from 4 to 13 and averaged 7. Two to five bedrock hollows located at heads of first-order channels, which entered the channels at angles usually less than 45°, were common initiation sites. These hollows are referred to as trigger hollows by Benda and Dunne (1987). Figure 2 shows the position of trigger hollows. None of the debris flows began by failure of the channel bed.

Travel distance and erosion

Forty of the 44 debris flows reached at least the mouths of first-order channels, an average distance of 250 m. Thirty-six continued to travel entirely through second-order channels, increasing their travel distance to an average of 550 m. Eighteen entered and traveled down at least part of a third-order channel, increasing their average distance to 1050 m. Eleven of the debris flows traveled the entire length of third-order channels and deposited at the junction with a fourth- or fifth-order channel. The maximum travel distance was 1600 m.

Channels with slopes greater than 10° (typically first- and second-order channels in Knowles Creek) were scoured to bedrock by debris flows in almost all cases. To estimate the volume of sediment stored in these channels, and therefore the amount eroded by passing debris flows, we measured bed deposits in four first- and two second-order channels (n = 3 per channel). These channels contain 5–10 m^3 of sediment of channel (average 8 m^3/m), and the sediment is dominated by colluvium (Benda and Dunne 1987; Benda 1988). A comparison of sediment sizes from several locations in Knowles Creek is shown in Fig. 3; these include bedrock hollows (n = 4); first-(n = 2), second-(n = 2), and fourth-order channels (n = 4); and debris-flow deposits (n = 3). These distributions are averages of surface counts (Wolman 1954) and bulk sieve analyses.

To estimate the volume of debris flows, we multiplied the average sediment volume stored in channels (8 m^3/m) by the length of channel traveled with a slope above 10°. Based on the sediment storage and channel lengths above, we found that the erosion of channel beds increased volumes of debris flows from an average of 450 m^3 at initiation to 2400 m^3 at the mouths of first-order channels. Debris-flow thicknesses and velocities in first-order channels were typically 3 m and 10 m/s. Debris flows that continued to erode throughout second-order channels increased their volumes to an average of 4800 m^3, while thicknesses and velocities were 4 m and 8 m/s. Third-order channels in the

TABLE 1. Observed debris-flow characteristics and predicted travel distances based on channel slope

Debris flow	Observed channel slope at deposition	Observed travel distance (m)
1	3	1485
2	7	1200
3	8	875
4	4	1500
5	3	1400
6	6	1085
7	2	810

	Predicted travel distance (m) for slope interval (°)				
Debris flow	1.5–2.5	2.5–3.5	3.5–4.5	4.5–5.5	5.5–6.5
1	2568	1656	1224	1032	948
2	2088	1752	1648	1544	1440
3	1392	1080	924	786	696
4	2736	1680	1440	1224	960
5	2500	1700	1400	800	600
6	1224	1014	768	552	504
7	960	576	516	456	396

	Error criteria (E) for slope interval (°)				
Debris flow	1.5–2.5	2.5–3.5	3.5–4.5	4.5–5.5	5.5–6.5
1	0.53	0.01	0.03	0.10	0.13
2	0.55	0.21	0.14	0.08	0.04
3	0.35	0.05	0.00	0.01	0.04
4	0.67	0.01	0.00	0.03	0.13
5	0.62	0.04	0.00	0.19	0.32
6	0.02	0.00	0.08	0.24	0.29
7	0.04	0.08	0.13	0.19	0.26
E =	0.24	0.09	0.09	0.13	0.16

Knowles Creek basin typically are less than 10° and were not significantly eroded by the passing debris flows. Owing to the increasing widths of third-order valley floors, debris-flow thicknesses decreased to 2 m; velocities decreased to less than 5 m/s because of decreases in channel gradient and decreases in flow thickness.

Deposition

Debris-flow deposition in the Knowles Creek basin usually occurred in channels where gradient gradually declined, or where the flow abruptly entered a low-gradient channel at tributary junctions. Debris flows deposited sediment and organic debris in channels and on floodplains, terraces, debris fans, and footslopes along alluvial valleys of third- through fifth-order streams. Deposits typically consisted of woody debris (300–1000 m^3) downstream of a 50–150 m length of unsorted sediments dominated by gravels, cobbles, and boulders.

Channel gradients at the downstream edge of the deposits ranged from 8° in third-order channels to 1° in fifth-order channels. These values measured in Knowles Creek are similar to those measured in other mountain regions where coarse-textured debris flows occur: 3°–10° in the Coast Range of Oregon (Swanson and Lienkaemper 1978); 4°–10° on Mt. Thomas, New Zealand (Pierson 1980); 3°–10° on Shodo-Shima Island, Japan (Ikeya 1981); and 3°–5° in Japan (Mizuyama 1981).

A second topographic factor affecting deposition of debris flows in Knowles Creek was the junction angle between the contributing and receiving channels. Junction angle is defined as the upstream angle between the tangent lines of two intersecting channels (Fig. 4). The reference tangent, which determines the angle, is defined by the receiving channel, i.e., the channel that continues downvalley. Debris flows that encountered large junction angles often collided with the opposite valley wall and deposited. The relationship between travel distance beyond a second-order to third-order junction and junction angle is shown in Fig. 5. These data are discussed in the following section.

Empirical model of debris flow travel distance and deposition in channels

Previous investigators (e.g., Johnson 1984) have identified the importance of sediment sizes and water content in debris flow. These factors appear to be relatively constant in the Tyee formation (Benda 1988) and the basalt basins (Benda 1986). With the aim of developing a model that did not require the rheological properties of debris flow, channel gradient and tributary junction angle were used to predict deposition.

The first criterion for predicting deposition was channel gradient. Of the 44 debris flows in Knowles Creek, only seven were suitable for analysis of channel gradient. These seven debris flows (debris flows 1–7, Tables 1 and 2)

TABLE 2. Observed and predicted travel distances for Knowles Creek and Washington Cascades

Debris flow	Observed travel distance (m)	Predicted travel distance (m)	Error (m)	Eq. [1]
		Knowles Creek		
1 s,j	1485	—	—	—
2 s,j	1200	—	—	—
3 s,j	875	—	—	—
4 s,j	1500	—	—	—
5 s,j	1400	—	—	—
6 s,j	1085	—	—	—
7 s,j	810	—	—	—
8 j	510	—	—	—
9 j	480	—	—	—
10 j	430	—	—	—
11 j	600	—	—	—
12 j	550	—	—	—
13 j	380	—	—	—
14 j	600	—	—	—
15	360	912	552	2.35
16	240	1008	768	10.24
17	240	648	408	2.89
18	620	480	−140	0.05
19	265	240	−25	0.01
20	733	648	−85	0.01
21	765	720	−45	0.01
22	762	602	−160	0.04
23	660	600	−60	0.01
24	1074	984	−90	0.01
25	660	500	−160	0.06
26	962	912	−50	0.00
27	1420	1300	−120	0.01
28	880	780	−100	0.01
29	483	418	−65	0.02
			E =	0.26
		Washington Cascades		
W1	2608	3260	652	0.06
W2	1620	1560	−60	0.00
W3	1896	1707	−189	0.01
W4	2760	600	−2160	0.61
W5	1200	600	−600	0.25
W6	3600	3700	100	0.00
			E =	0.16

NOTE: s, used in determining slope for deposition; j, used in determining junction angle for deposition.

deposited in straight reaches with gradually declining channel gradients. Their deposition was not complicated by collisions with valley walls at tributary junctions. To determine the slope that best predicted deposition and hence travel distance, we compared actual travel distances of the seven debris flows with travel distances predicted on a 1:24 000 topographic map (12 m or 40 ft contour intervals). Deposition was predicted using channel-gradient intervals of 1.5°–2.5°, 2.5°–3.5°,..., 5.5°–6.5°. Predicted travel distance of each of the seven flows was determined by measuring the map distance from the initial failure to the midpoint between the two contour crenulations whose gradient falls within the chosen interval. Results are listed in Table 1. The interval that gave the best agreement between observed and predicted distances was obtained by using the objective function:

$$[1] \quad E_i = \frac{1}{n}\sqrt{\sum_{j=1}^{n} \left[\frac{P_j - O_j}{O_j}\right]^2}$$

where E_i is the error resulting from the choice of the ith gradient interval, and P_j and O_j are, respectively, the predicted and observed travel distances for the jth debris flow. The objective function was minimized when a slope interval of 3.5°–4.5° was used. However, the minimum error is not well defined in one slope interval (Table 1) but is more broadly defined by the two intervals between 2.5° and 4.5°; therefore, a critical slope of 3.5° is suggested.

A second topographic criterion was developed to account for deposition as a result of collisions with the opposite valley wall at channel junctions. The distance traveled by debris flows beyond second- to third-order tributary junctions

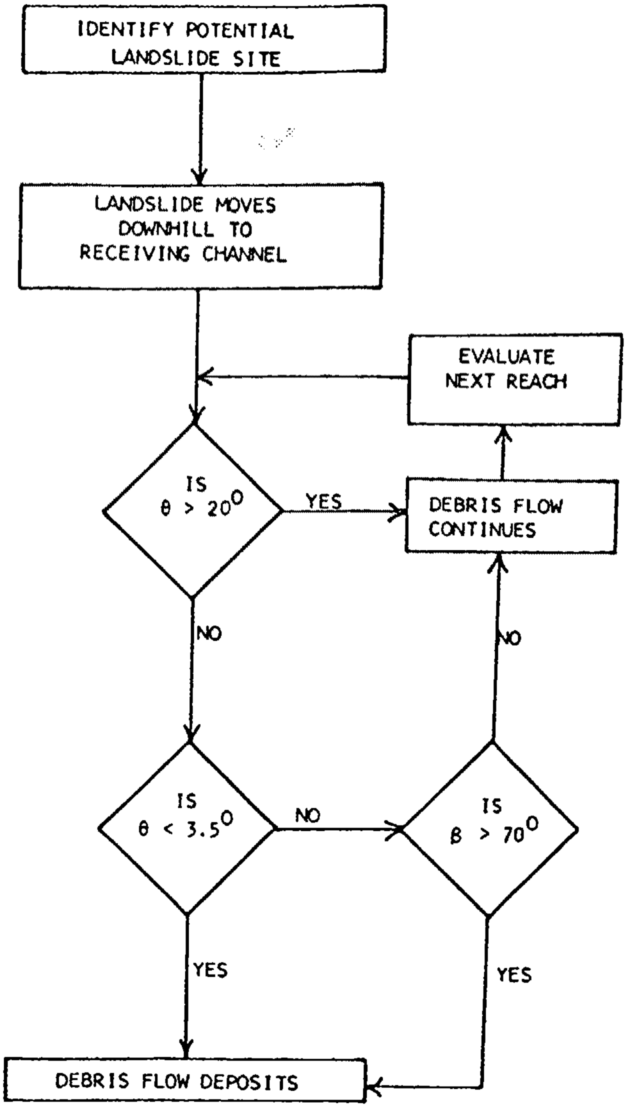

FIG. 6. Flow chart for predicting deposition of debris flows.

is shown in Fig. 5. The data in Fig. 5 include debris flows 1–7 used in the slope analysis and seven other debris flows (8–14, Table 2), which deposited on channel gradients greater than 3.5° at second- to third-order junctions with angles greater than 70°. Therefore, a channel-junction angle of greater than 70° predicted deposition at these sites (Fig. 5). In most cases of deposition at a channel junction, at least part of the deposit extended downstream between 50 and 150 m. The importance of junctions in causing deposition was shown in previous work (Swanson and Lienkaemper 1978).

A flow chart for the empirical model to predict debris-flow deposition is shown in Fig. 6. Analysis begins by identifying the location of a potential landslide site; this is done independently of the debris flow analysis; for example, by the method of Burroughs (1984).

Next, the gradient of the receiving channel is evaluated. In the study area some hollows intersect steep first-order channels at angles greater than 70°. Landslides originating from these hollows may temporarily deposit in the channel; subsequent failure of this material may initiate a debris flow. This form of initiation was not observed in this study; however, it is included in the model for completeness. The minimum slope necessary for failure of landslide debris in a channel was estimated from an infinite-slope analysis (Sidle *et al.* 1985). Soil was assumed cohesionless because of the breakup of the soil and its reinforcing network of roots following the initial landslide; saturation was also assumed. Using an effective angle of internal friction of 38° and a saturated unit weight of 1.9 g/cm^3 (Schroeder and Alto 1983), we estimated that a slope of 20° caused failure of landslide debris in first-order channels.

Following the evaluation of steep channels ($\theta > 20°$), subsequent reaches are evaluated until either a channel gradient of less than 3.5° or a junction angle of greater than 70° is encountered. When either of these criteria are satisfied, deposition is predicted. When a contour interval contains

TABLE 3. Observed and predicted travel distances for debris flows measured on air photos

Debris flow	Approximate travel distance (m)	Predicted travel distance (m)
	Knowles Creek	
30	240	240
31	380	380
32	220	220
33	360	360
34	600	600
35	890	890
36	480	480
37	620	620
38	240	240
39	960	960
40	840	840
41	910	910
42	1300	1300
43	1200	1200
44	1000	1000
	basalt basins	
B1	360	960
B2	1100	1100
B3	720	720
B4	550	550
B5	840	840
B6	1130	1130
B7	288	288
B8	760	760
B9	1130	1130
B10	760	760
B11	1050	1050
B12	840	840
B13	890	890
B14	290	290
B15	780	780
B16	1080	1080
B17	550	550
B18	430	2300
B19	960	960
B20	920	920
B21	1080	1080
B22	550	550
B23	770	770
B24	1560	1560
B25	840	1320
B26	600	600
B27	550	550
B28	630	630
B29	670	670

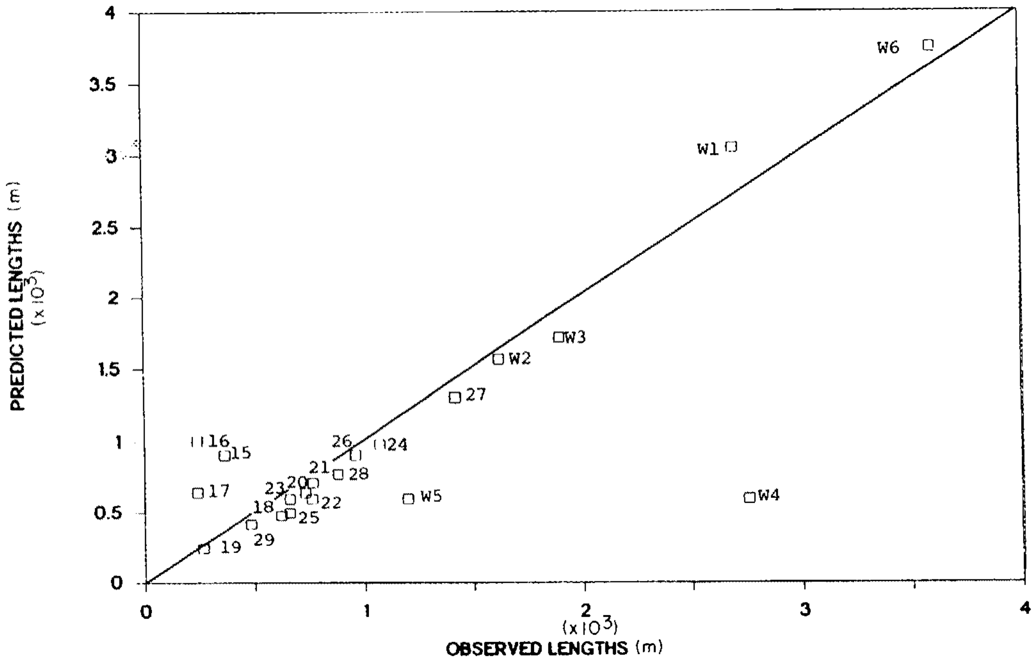

FIG. 7. Predicted and observed travel distances of debris flows in Knowles Creek and Washington Cascades. Numbers on graph correspond to debris flows in Table 2.

a channel junction, the junction angle should be evaluated first.

When deposition is predicted based on channel gradient, the point of deposition used here is the midpoint between two contour crenulations. When deposition is predicted based on channel-junction angle, the point of deposition is at the junction.

The approximate volume of the debris flow is determined by measuring the length of channel traveled with a gradient greater than 10°. This length multiplied by the average amount eroded of 8 m^3/m, plus the volume of the original failure, gives the estimated volume of the flow.

Test of the model

The model described above was used to predict deposition and hence travel distance of 15 of the debris flows in the Knowles Creek basin (flows 15–29) and the six flows in Washington. The results are shown in Table 2 and Fig. 7.

The model made large overpredictions for three flows in Knowles Creek basin (flows 15, 16, and 17, Table 2). These debris flows deposited within first-order channels with slopes between 14° and 18°. The apparently premature deposition of these three flows demonstrates the limitations of the empirical model.

The model underpredicted 12 of 15 debris flows in the Knowles Creek basin by approximately 50 to 150 m (Fig. 7). This is because the model predicts deposition at tributary junctions and it does not account for the debris flow traveling beyond the junction because of momentum. Linking the model to that of Takahashi and Yoshida (1979) would account for some of the travel by debris flows past junctions and thereby increase the accuracy of the procedure.

The six flows in Washington are also summarized in Table 2 and plotted in Fig. 7. Debris flow W3 in Washington traveled the entire length of the confined channel and deposited approximately 300 m downstream on an alluvial fan. The model accurately predicted the travel of the flow to the end of the confined channel but was not applied on the fan, thus yielding the underprediction. This is another case where linking this model to that of Takahashi and Yoshida (1979) would be useful.

The underprediction of travel distances for debris flows W4 and W5 is probably because the model does not explicitly account for momentum of the flow. The longitudinal profiles of these channels are bedrock stair-stepped, having reaches with low gradients between reaches of higher gradients. The model predicts deposition at the first reach with a gradient less than 3.5°. In these cases, the momentum of the flows carries them over the reaches of low gradient into the downstream reaches of higher gradient. Therefore, where channels are stair-stepped, the model should be applied with caution. A conservative approach would be to predict deposition only after 300 m (2 × 150 m, twice the length of a long deposit) of a channel with a gradient less than 3.5°.

A lower level of accuracy of the model may be sufficient for certain forestry applications in remote areas, such as delineating source areas of debris flows that would travel through or deposit in fish-bearing streams. For this purpose, the debris flows measured from air photos, fifteen in Knowles Creek (flows 30–44, Table 3) and the 29 in basalt basins (B1–B29, Table 3), provide an additional test. On these flows the data available are the approximate travel distances, as shown by the destruction of streamside vegetation on 1:24 000 aerial photos. The model accurately predicted the approximate travel distance for all 15 debris flows in Knowles Creek and for 26 of 29 debris flows in the basalt basins (Table 3). All of the debris flows that were accurately predicted deposited near tributary junctions. Again, there is typically a 50–150 m deposit, which may extend downstream under a closed canopy and is not predicted by the model. The three debris flows in the basalt basins that were not accurately predicted deposited on slopes greater than 10° (flows B1, B18, and B25, Table 3).

Application of the model

As pointed out earlier, there are several other factors important in controlling debris flows. The model presented here is based only on the geometry of the channel network; it does not explicitly account for rheological properties or mechanics of the flow. Therefore, like any empirical model, it should be field checked and (or) calibrated prior to use in other areas. The values of the channel gradient and junction angle necessary for deposition may need to be adjusted, based on field measurements obtained in the area of interest. Likewise, the volume of sediment stored in channels and erosional characteristics of the debris flows need to be checked if volume prediction is desired.

The previous discussions of Washington debris flows W3, W4, and W5 suggest other considerations may be needed in applying the model. All of these points indicate the need for field investigations following a map-based analysis, particularly when resource values or hazards are high.

The model should be useful to geologists, foresters, and fishery biologists to identify potential for impacts to stream crossings and fish habitat. In addition, it could be combined with existing models of debris-flow runout on alluvial fans for hazard zonation (e.g., Takahashi and Yoshida 1979).

Conclusions

Debris flows are a serious form of mass wasting of increased concern in the Pacific Northwest. They represent significant hazards to life, property, and other resources, such as streams and fish habitat. The empirical model presented here predicts travel distances and deposition sites of debris flows in confined mountain channels in the Oregon Coast Range, based on easily obtained map and air-photo measurements. It can be used by engineers and resource planners to recognize and zone hazard areas. In addition, the model can be used by geomorphologists and land planners to assist in predicting erosion and deposition of coarse-bed material along mountain-stream channels. The model should be field checked and calibrated for use in other areas.

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BALDWIN, E.M. 1964. Geology of Oregon. Edwards Brothers Inc., Ann Arbor, MI.

BENDA, L. 1985. Delineation of channels susceptible to debris flows and debris floods. *In* Proceedings of the International Symposium on Erosion, Debris Flow and Disaster Prevention. Tsukuba, Japan. *Edited by* A. Takei. pp. 195–202.

——— 1986. The physical characteristics and behaviour of debris flows in three land type associations of the Siuslaw National Forest. Project Report of the Pacific Northwest Forest and Range Research Station, U.S. Forest Service, RWU-1705.

——— 1988. Debris flows in the Tyee formation of the Oregon Coast Range. Masters Thesis, University of Washington, Seattle, WA.

BENDA, L., and DUNNE, T. 1987. Sediment routing by debris flows. *In* Erosion and sedimentation in the Pacific rim. *Edited by* R.L. Beschta, T. Blinn, G.E. Ice, and F.J. Swanson. IAHS Publication No. 165, pp. 213–223.

BENDA, L., and ZHANG, W. 1989. The hydrological and geomorphological characteristics of landslide/dam-break floods in the Cascade mountains of Washington. Transaction of the American Geophysical Union, Abstract no. H52A-3, p. 1124.

BURROUGHS, E.R. 1984. Landslide hazard rating for portions of the Oregon Coast Range. *In* Symposium on Effects of Forest Land Use on Erosion and Slope Stability. Environment and Policy Institute, East–West Center, University of Hawaii, Honolulu, HI. pp. 265–274.

CHOW, V.T. 1959. Open-channel hydraulics, McGraw-Hill Book Company, New York, NY.

DIETRICH, W., and DUNNE, T. 1978. Sediment budget for a small catchment in mountainous terrain. Zeitschrift für Geomorphologie. N.F. Supplementband **29**: 191–206.

EISBACHER, G.H., and CLAGUE, J.J. 1984. Destructive mass movements in high mountains: Hazards and Management. Geological Survey of Canada, Ottawa, Ont. Paper 84-16.

HUNGR, O., MORGAN, G.C., and KELLERHALS, R. 1984. Quantitative analysis of debris torrent hazards for design of remedial measures. Canadian Geotechnical Journal **21**: 663–677.

IKEYA, H. 1981. A method for designation for area in danger of debris flow. *In* International Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands. IAHS–AISH Publication 132, pp. 576–588.

IVERSON, R.M., and MAJOR, J.J. 1986. Groundwater seepage vectors and the potential for hillslope failure and debris flow mobilization. Water Resources Research **22**: 1543–1548.

JOHNSON, A.M. 1984. Debris flow. *In* Slope instability. *Edited by* D. Brunsden and D.B. Prior. Wiley and Sons, New York, NY. pp. 257–361.

MIZUYAMA, T. 1981. An intermediate phenomenon between debris flow and bedload transport. *In* International Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands. IAHS–AISH Publication 132, pp. 212–224.

MIZUYAMA, T., IKEYA, H., and IMAMURA, R. 1984. Methods for zoning debris flow vulnerable areas. *In* Symposium on Effects of Forest Land Use on Erosion and Slope Stability. Environment and Policy Institute, East-West Center, University of Hawaii, Honolulu, HI. pp. 281–288.

PIERSON, T. 1980. Erosion and deposition by debris flows at Mt. Thomas, North Canterbury, New Zealand. Earth Surface Process, **5**: 227–247.

RENEAU, S.L., and DIETRICH, W.E. 1987. The importance of hollows in debris flow studies: Examples from Marin County, California. *In* Debris Flows/Avalanches: Process, Recognition, and Mitigation. Reviews in Engineering Geology, Geological Society of America, Vol. 7.

SCHROEDER, W.L., and ALTO, J.V. 1983. Soil properties of slope stability analysis; Oregon and Washington coastal mountains. Forest Science, **29**: 823–833.

SIDLE, R.C., PEARCE, A.J., and O'LOUGHLIN, C.L. 1985. Hillslope Stability and Landuse. American Geophysical Union, Water Resources Monograph 11.

SWANSON, F.J., and LIENKAEMPER, G.W. 1978. Physical consequences of large organic debris in Pacific Northwest Streams. U.S.D.A. Forest Service, Gen. Tech. Report PNW-69.

SWANSON, F.J., BENDA, L., DUNCAN, S., GRANT, G., MEGAHAN, W., REID, L., and ZEIMER, R. 1987. Mass failures and other processes of sediment production in Pacific Northwest landscapes. *In*: Proceedings, Streamside Management: Forestry-Fishery Interactions. *Edited by* E.O. Salo, T.W. Cundy, University of Washington, Seattle, WA. pp. 9–38.

SWANSTON, D.N. 1980. Influence of Forest and Rangeland Management on Anadromous Fish Habitat in Western North America. No. 2 Impacts of Natural Events. *Edited by* William R. Meehan. Pacific Northwest Forest and Range Experiment Station. U.S. Forest Service, Portland, OR.

TAKAHASHI, T., and YOSHIDA, H. 1979. Study on the Deposition of Debris Flows, Part I: Deposition due to abrupt change in bedslope. Annuals, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan, **22**: B-2.

TSUKAMOTO, Y., OHTA, T., and NOGUCHI, H. 1982. Hydrological and geomorphological studies of debris slides on forested hillslopes in Japan. *In* Recent Develoments in the Explanation and Prediction of Erosion and Sediment Yield. IAHS Publication No. 137, pp. 89–98.

WOLMAN, M.G. 1954. A method of sampling coarse riverbed material. Transactions of the American Geophysical Union, **35**: 951–956.